

Long range phenomena in heavy ion collisions observed by the PHOBOS experiment

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The PHOBOS experiment at RHIC has measured large samples of Au+Au and Cu+Cu collisions using a detector with uniquely large angular acceptance. These data enable studies of particle production over a very wide pseudorapidity interval which reveal unexpected features. In the analysis of correlations with a high- p_T trigger particle ($p_T > 2.5$ GeV/c) a ridge extending at least 4 units of pseudorapidity was found. The results on forward-backward and two-particle correlations suggest that particles are produced in very large clusters which are wider in pseudorapidity than is expected for isotropic decays. Explanation of these experimental results requires models in which both short-range and long-range correlations are present.

Since the year 2000 at the Relativistic Heavy Ion Collider (RHIC), collisions of heavy ions at the highest energies have been measured and analysed. Several phenomena found in these studies manifest creation of a new type of matter, strongly interacting Quark-Gluon Plasma (sQGP). Most noticeable are the absorption of partons observed as suppression of high- p_T particles or jets and the collective effects visible as a strong elliptic flow¹. Better understanding of properties of the matter created in heavy ion collisions and a search for signs of potential phase transition require detailed analysis of many observables and studies of correlations between them.

The PHOBOS experiment measured all types of collisions available at RHIC using a detector optimized for registering charged particles² in almost full solid angle - with the multiplicity detector covering uniquely wide range $|\eta| < 5.4$. In the spectrometer, momenta of about 1% of charged particles were determined. Using this detector it was possible to measure the yields of particles with extremally small transverse momenta (starting from 30 MeV/c for pions). The comparison of yields of charged particles at high- p_T in $d + Au$ and $Au + Au$ collisions clearly shows that partons created in hard scattering of quarks or gluons interact in the dense matter created in the central $Au + Au$ collisions. Usually at least one of back-to-back emitted partons is stopped and only a jet or a high- p_T particle originating from the second parton is registered.

The analysis² of the correlations between a trigger particle with $p_T > 2.5$ GeV/c and other

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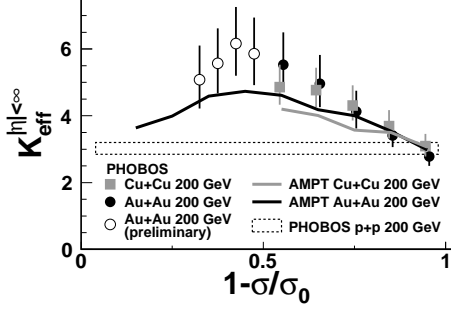


Figure 1: The effective size of the clusters corrected for the acceptance effects, as a function of the fractional cross section, i.e. obtained for similar geometry of $Au + Au$ and $Cu + Cu$ collisions. The cluster parameters obtained for elementary $p + p$ collisions and the results of the same reconstruction procedure performed on the events from AMPT generator are shown for comparison.

charged particles as a function of the difference of pseudorapidity and azimuthal angle, $\Delta\eta$ and $\Delta\phi$, allows to study the interaction of the stopped parton with the medium. In the central $Au + Au$ collisions the yield of particles correlated with the high- p_T trigger particle is larger than in the $p + p$ interactions. In the *near side*, $|\Delta\phi| \approx 0 \pm 1$, a ridge extending up to the end of acceptance range ($-4 < \Delta\eta < 2$) is present. It can be described as an additional yield which adds uniformly in η to the yield observed in $p + p$ interactions. In the *away side*, $\Delta\phi \approx \pi \pm 2$, such additional yield is even larger. Analysis of these yields as a function of centrality shows that they are the largest in central collisions and decrease for peripheral collisions. At $N_{part} \approx 80$ the difference between $Au + Au$ and $p + p$ for the *near side* drops to zero.

The correlations between all charged particles registered in the PHOBOS multiplicity detector were studied in a very wide range, $|\eta| < 3$, for elementary $p + p$ interactions (at 200 GeV and 410 GeV³) and nuclei collisions, $Cu + Cu$ and $Au + Au$ at 200 GeV^{4,5}. They are represented by a correlation function:

$$R(\Delta\eta, \Delta\phi) = \left\langle (n - 1) \left(\frac{\rho_n^H(\Delta\eta, \Delta\phi)}{\rho_{mixed}^H(\Delta\eta, \Delta\phi)} - 1 \right) \right\rangle$$

where $\rho(\eta_1, \eta_2, \phi_1, \phi_2)$ is the charged pair density distribution for measured events (in the numerator) or for uncorrelated pairs taken from different events (in the denominator). In the further analysis the function integrated over one of the variables, $R(\Delta\eta)$ or $R(\Delta\phi)$, is used. The first of them has a maximum at $\eta \approx 0$ which is expected for short range correlations. It is thus natural to describe particle production as a two-step process: production of some intermediate objects, clusters, which then decay into finally observed particles⁶. Using the correlation function $R(\Delta\eta)$ it is possible to extract the parameters of the clusters: K_{eff} , the effective cluster size, and δ , width of the two-particle correlation. It is worth to note that even for very large acceptance, six pseudorapidity units, available in PHOBOS, acceptance corrections are large. Already in the elementary interactions³ the cluster size is large, $K_{eff} \approx 3$. Even larger values, up to $K_{eff} \approx 6$, are found in nuclei collisions^{4,5}, as shown in Fig.1. The width of the clusters (shown later in Fig.4) is also large, exceeding that expected for isotropic decay at rest. We observe the same cluster parameters for $Cu + Cu$ and $Au + Au$ collisions with similar geometries even if the number of nucleons participating in the collisions and total multiplicities are much different^{4,5}.

Also, the correlation function $R(\Delta\phi)$ can be explained by the cluster model. However, a simple assumption that clusters' momenta can be randomly generated from a universal function reproducing only global $dN/d\eta$ and dN/dp_T distributions leads to a shape totally different from that measured experimentally. An agreement can be achieved only after enforcing transverse momentum conservation (by slightly modifying momenta to ensure $\Sigma p_T = 0$) as can be seen in Fig.2.

The large acceptance of the PHOBOS detector allows to measure forward-backward correlations at large distances. In this study, an asymmetry variable $C = (N_B - N_F)\sqrt{N_F + N_B}$ is used, where N_B and N_F denote the number of charged particles measured in two pseudorapidity bins, symmetric with respect to $\eta = 0$, at negative and positive η , respectively⁷. This variable is insensitive to the dependence of total multiplicity on centrality of the collision (that is enforced

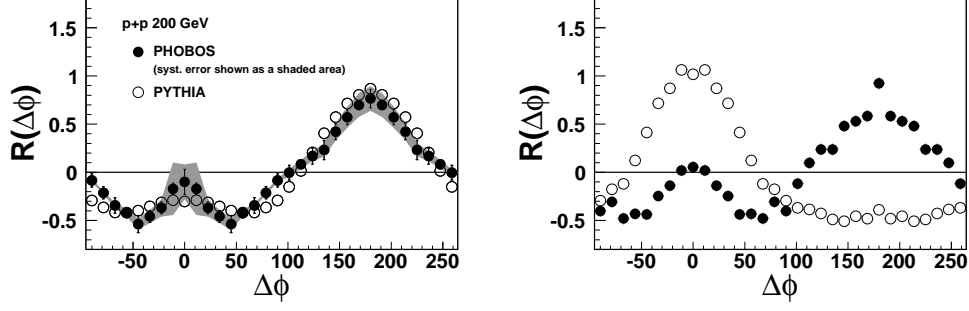


Figure 2: Two-particle correlation functions $R(\Delta\phi)$ obtained for the experimental data (left) and for generated events with identical clusters (decays: $\omega(782) \rightarrow \pi^+\pi^-\pi^0$) (right). In the right plot the correlation for events with randomly generated clusters (open circles) and modified so that sum of all transverse momenta is zero (full circles) are compared.

ing $\langle N_B \rangle = \langle N_F \rangle$), but the variance σ_C^2 measures the strength of multiplicity fluctuations. For purely statistical fluctuations we obtain $\sigma_C^2 = 1$. The PHOBOS Collaboration has measured σ_C^2 as a function of the width of pseudorapidity bin, $\Delta\eta$, and the position of bin center, η . σ_C^2 is larger than 1 and increases when η and especially $\Delta\eta$ increase⁷. This agrees qualitatively with the expectation from the cluster model, in which the observed dependencies are explained by acceptance effects. However, in this case it is not possible to extract both parameters of the clusters at the same time, as for large and wide clusters these dependencies may look similar as for small but narrow clusters⁸. Unexpectedly, but consistently with the trends observed for 2-particle correlations, the values of σ_C^2 found for central $Au + Au$ collisions are smaller than for peripheral collisions (see Fig.3), indicating different effective cluster sizes (and possibly also δ width).

The centrality dependence of σ_C^2 values, shown in Fig.3, is not well reproduced by the models of particle production: UrQMD⁹ has wrong centrality dependence, HIJING¹⁰ gives in both cases the same values and AMPT¹¹ predicts correct trend, but underestimates σ_C^2 . The best agreement¹² is observed for the Wounded Nucleon Model¹³ which assumes that the nucleons taking part in the collision are the source of the particles which are produced according to a universal fragmentation function, asymmetric in η and about 10 pseudorapidity units wide, extracted from the data on $d + Au$ collisions. The fluctuations observed as large values of σ_C^2 are a sum of these present already in $p + p$ interactions (possibly from production of clusters) and those generated by the fluctuations of the number of wounded nucleons, in forward and backward moving nuclei¹².

The Wounded Nucleon Model may be used to describe not only forward-backward fluctuations, but also 2-particle correlations. In this case, predictions are less precise, as it is more difficult to include short range correlations (from $p + p$). Obviously, 2 wounded nucleons should fragment into clusters which then decay into final particles. As an approximation identical clus-

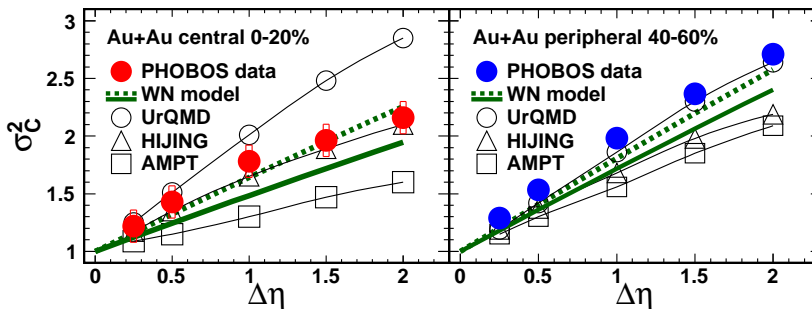


Figure 3: The values of σ_C^2 as a function of pseudorapidity bin width $\Delta\eta$ for central and peripheral $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Experimental results are compared with predictions from several models.

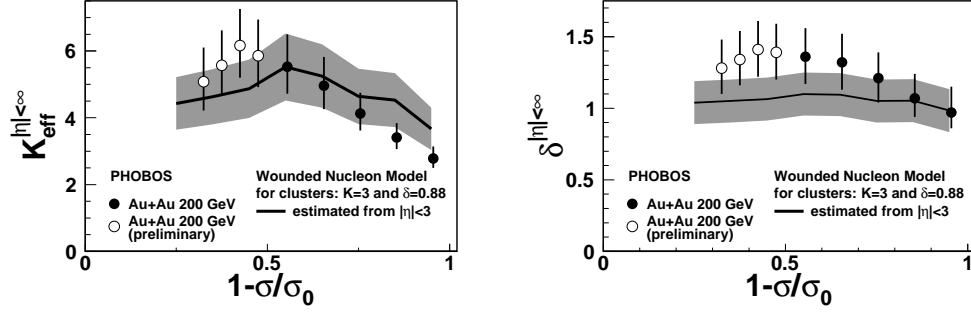


Figure 4: The effective cluster size (left) and the width parameter δ (right) for $Au + Au$ collisions compared with the predictions from the Wounded Nucleon Model in which we assume fragmentation of the wounded nucleons into clusters similar to those observed in $p + p$ interactions.

ters with $K_{eff} = 3$ and $\delta = 0.88$, effective parameters found in $p + p$ interactions³, can be used. The fragmentation function into clusters should have similar shape (but K_{eff} times smaller integral) as for fragmentation into particles. These assumptions allow to obtain Wounded Nucleon Model predictions shown in Fig.4. Again the main trends are reproduced: the reconstructed cluster size becomes larger for peripheral than for central collisions and the width parameter δ increases. Discrepancies may be due to the fact, that in reality we have a mixture of clusters with various sizes and widths and convolution with wounded nucleons fluctuations gives in this case different reconstruction results than for identical clusters.

In the studies of correlations measured over a wide range of pseudorapidity, strong long-range effects were found. There is a long ridge in the correlation with a high- p_T trigger particle, clusters found in the 2-particle correlations are large and unexpectedly wide. The correlation in the azimuthal angle seems to be determined by the global momentum conservation. Forward-backward and 2-particle correlations can be at least qualitatively described by the Wounded Nucleon Model, in which particles are additionally correlated at large distances because they are emitted according to a fragmentation function, which extends over 10 pseudorapidity units.

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